THE LYMAN-α FOREST ACCORDING TO LUQAS

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We use the LUQAS sample of 27 high resolution, high signal-to-noise QSO absorption spectra (Kim et al. 2004) and the results from Croft et al. (2002) together with a suite of high-resolution hydro-dynamical simulations run with the GADGET-II code, to infer the linear dark matter power spectrum on scales of $\sim 0.3 - 30$ Mpc at $z = 2.125$ and at $z = 2.72$.

1 Introduction

The Lyα forest in QSO absorption spectra has been used to probe dark matter power spectrum by a number of authors (e.g. Croft et al. [1]; Gnedin & Hamilton [2]; Viel, Haehnelt & Springel [13] and references therein). The Lyα forest is sensitive to fluctuations in the DM density on scales of a few Mpc. It can thus be used to investigate the possible cut-off of the DM spectrum which is expected if the dark matter were warm dark matter, it can give constraints on the matter fraction in neutrinos and allows to investigate the gravitational growth of structure and possibly the redshift evolution of dark energy (Viel et al. [10]; Mandelbaum et al. [6]; Lidz et al. [5]). Verde et al. [9] combined the Lyα forest results of Croft et al. with the CMB results of WMAP and concluded that there is evidence for a running spectral index and for a tilt in the primordial power spectrum. However, a recent analysis by Seljak et al. [7] argued that the errors are larger and the effective optical depth is smaller than that assumed by Verde et al. Seljak et al. concluded that there is no evidence for a running spectral index or for a tilt of the primordial power spectrum. We briefly discuss here the flux power spectrum of the LUQAS sample (Kim et al. [3]), a set of high resolution QSO absorption spectra, and compare it to the recently published flux power spectrum obtained for a large sample of low-resolution SDSS spectra (McDonald et al. [4]). We will further discuss the linear dark matter power spectrum which Viel et al. [13] obtained from the LUQAS flux power spectrum using the effective bias method proposed by Croft et al. [1]. Implications for the rms fluctuation amplitude σ_8 and the primordial index n are also discussed.

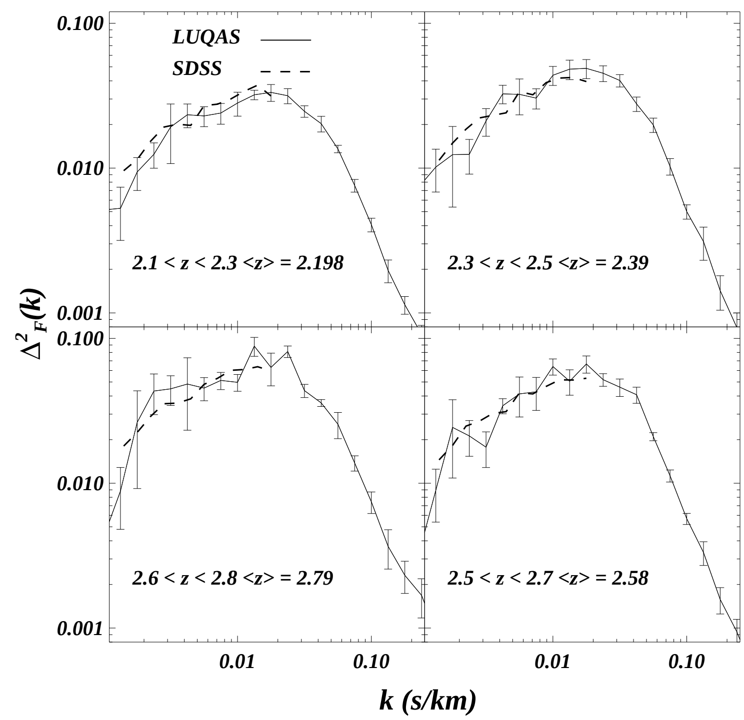

Figure 1: Comparison between the flux power spectrum of the LUQAS sample (continuous line with error bars) and the recent results for a large sample of SDSS spectra by McDonald et al. 2004 (dashed line). Note that the SDSS data refer to their table 3 including the background contribution.

2 The LUQAS sample

The LUQAS sample[a] (Large Sample of UVES Quasar Absorption Spectra) consists of spectra of 27 QSOs taken with the Ultra-Violet Echelle Spectrograph (UVES) on VLT. Most of the spectra have been taken as part of the Large ESO Observing programme UVESLP (P.I.: J. Bergeron). The median redshift of the sample is $z = 2.25$ and the total redshift path is$\Delta z = 13.75$. The typical signal-to-noise ratio is ~ 50 and the pixel size is 0.05 Å. For a more detailed description of the sample and the data reduction we refer to Kim et al. [3]. In Figure 1 we compare the 1D flux power spectrum of four subsamples of LUQAS at different redshifts (continuous curves) with the flux power spectrum obtained by McDonald et al. [4] from a large sample of low-resolution SDSS spectra (dashed curves).

There is reasonable good agreement between the two estimates of the flux power spectrum over a wide range of wave-numbers, in all four redshift bins. Note that due to the significantly higher resolution the LUQAS sample can constrain the matter power spectrum all the way to the thermal cutoff ($k > 0.01$ s/km). At these small scales the estimate of the SDSS sample is affected by its low resolution. The statistical errors of the SDSS sample are significantly smaller but the systematic uncertainties are larger than the statistical errors (Kim et al. [3], McDonald et al. [4]). The flux bispectrum of the LUQAS sample has been presented in Viel et al. [12]. Note that the large discrepancy between the two samples claimed in McDonald et al. was mainly due to an an erroneous shift of the flux power spectrum by half a bin-size in log k in Kim et al.

[a] Tables of the flux power spectrum are available at: www.ast.cam.ac.uk/~rtnigm/luqas.html. Please note that the k-values of tables 3 and 5 of Kim et al. [3] had been erroneously shifted by half a bin-size in log k (erratum in press). Corrected tables can also be found in astro-ph/0308103.

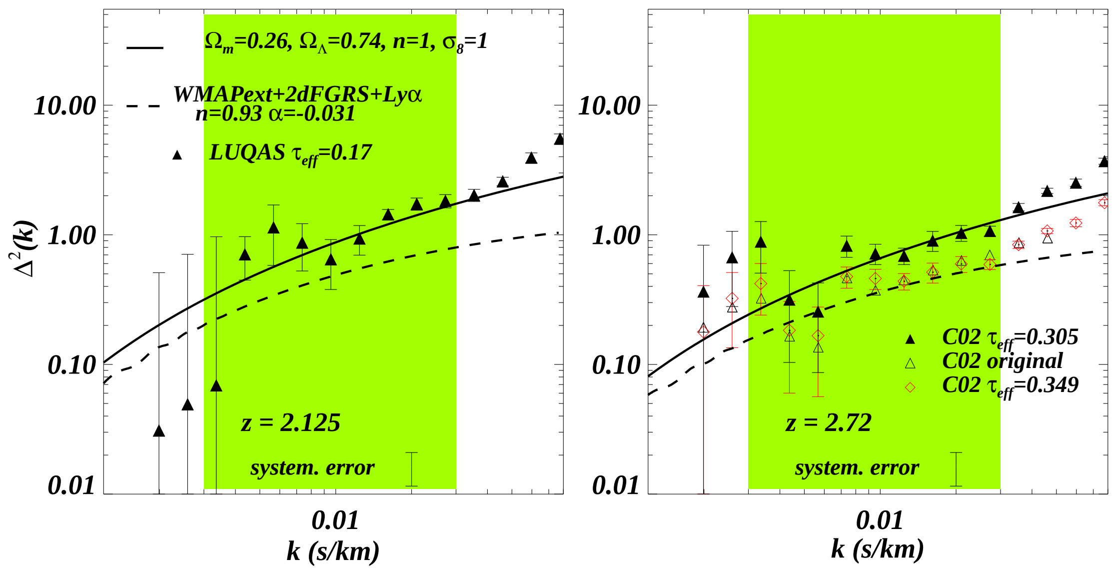

Figure 2: The recovered linear dark matter power spectrum at two different redshifts. At $z = 2.125$ using the LUQAS sample (left panel) and at $z = 2.72$ using the Croft et al. (2002) sample (right panel). The filled triangles have been obtained with an effective optical depth derived from high resolution spectra and from hydro-simulations with $T_0 = 10^{4.15}$ K and $\gamma = 1.6$. In the right panel we overplot the original result from Croft et al. (empty triangles) and a re-analysis of their data with the effective optical depth they assumed (diamonds). Continuous black line shows a model which is a good fit to our data. The dashed line represents a model with a running spectral index with best fitting values suggested by the WMAP experiment (Table 10, Spergel et al. 2003). The yellow rectangles indicate the range of wavenumbers used in our analysis.

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3 Inferring the linear dark matter power spectrum

The method we use to infer the linear dark matter power spectrum has been proposed by Croft et al. [1] (but see Gnedin & Hamilton [2]). It uses numerical simulations to calibrate the relation between flux power spectrum and matter power spectrum. It then assumes that the flux power spectrum $P_F(k)$ at a given wavenumber k depends linearly on the linear real space matter power spectrum $P(k)$ at the same wavenumber and that both can be related by a simple bias function $b(k)$ as $P_F(k) = b^2(k)\,P(k)$.

We have run a suite of hydro-dynamical simulations with varying cosmological parameters, particle numbers, resolution, boxsize and thermal histories using a new version of the parallel TreeSPH code GADGET, in order to explore the different systematics and statistical errors.

In Figure 2 we show the results of our analysis in terms of $\Delta^2(k) = P(k)\,k^3/(2\pi^2)$ for the LUQAS sample (left panel) at $z = 2.125$ and for the Croft et al. sample (right panel) at $z = 2.72$. The filled triangles represent the recovered linear dark matter power spectrum using values of $\tau_{\rm eff}$ suggested by high-resolution spectra.

The dashed curves in Figure 2 represent the best fitting running spectral index model of Spergel et al. [8] which is a fit to WMAP, CBI, ACBAR, 2dFGRS and the Lyman-α forest data, while the continuous line is a good fit to our data points.

In order to minimise uncertainties due to continuum fitting and metal lines, and to avoid dealing with the problematic thermal cut-off at small scales, we have only used the range of wavenumbers $0.003 < k\,(\mathrm{s/km}) < 0.03$ for our quantitative analysis, which corresponds roughly to scales 0.3-30 Mpc.

The main results can be summarized as follows. With the same assumptions for effective optical depth, density-temperature relation, and cosmology, our inferred linear matter power spectrum (empty diamonds right panel) agrees very well with that inferred by Croft et al. [1] (empty triangles right panel).

We confirm previous results that the inferred rms amplitude of density fluctuations depends strongly on the assumed $\tau_{\rm eff}$. It increases by 20% if we assume an optical depth of $\tau_{\rm eff} = 0.305$ a value indicated form high-resolution absorption spectra. We find, however, a dependence on $\tau_{\rm eff}$ which is weaker than that of Croft et al. [1] and stronger than that of Gnedin & Hamilton [2] . The decrease of the amplitude of the flux power spectrum between $z = 2.75$ and $z = 2.125$ is consistent with that expected due to the decrease of $\tau_{\rm eff}$ and the increase of the amplitude of matter power spectrum due to gravitational growth.

Our estimate of the systematic uncertainty (error bars in the bottom part of the two panels in Figure 2) of the rms fluctuation amplitude of the density ($\sim 14.5\%$) is a factor 3.5 larger than our estimate of the statistical error ($\sim 4\%$). The systematic uncertainty is dominated by the uncertainty in the mean effective optical depth and by the uncertainties between the numerical simulations of different authors. Reducing the overall errors will thus mainly rely on a better understanding of a range of systematic uncertainties.

By combining the constraint on the amplitude of the DM power spectrum on large scale from COBE (assuming that there is no contribution from tensor fluctuations) with the constraint from the high-resolution Lyman-α forest data on small scales we obtain $n = 1.01\ (\Omega_{\rm 0m}h^2/0.135)^{-0.35} \pm 0.02$(statistical) $\pm\ 0.06$(systematic) for the spectral index. The corresponding rms fluctuation amplitude is, $\sigma_8 = 0.93 \pm 0.03$(statistical) $\pm\ 0.09$(systematic).

Thus, for values of the mean optical depth favoured by high-resolution spectra, the inferred linear power spectrum is consistent with a ΛCDM model with a scale-free ($n = 1$) primordial power spectrum.

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